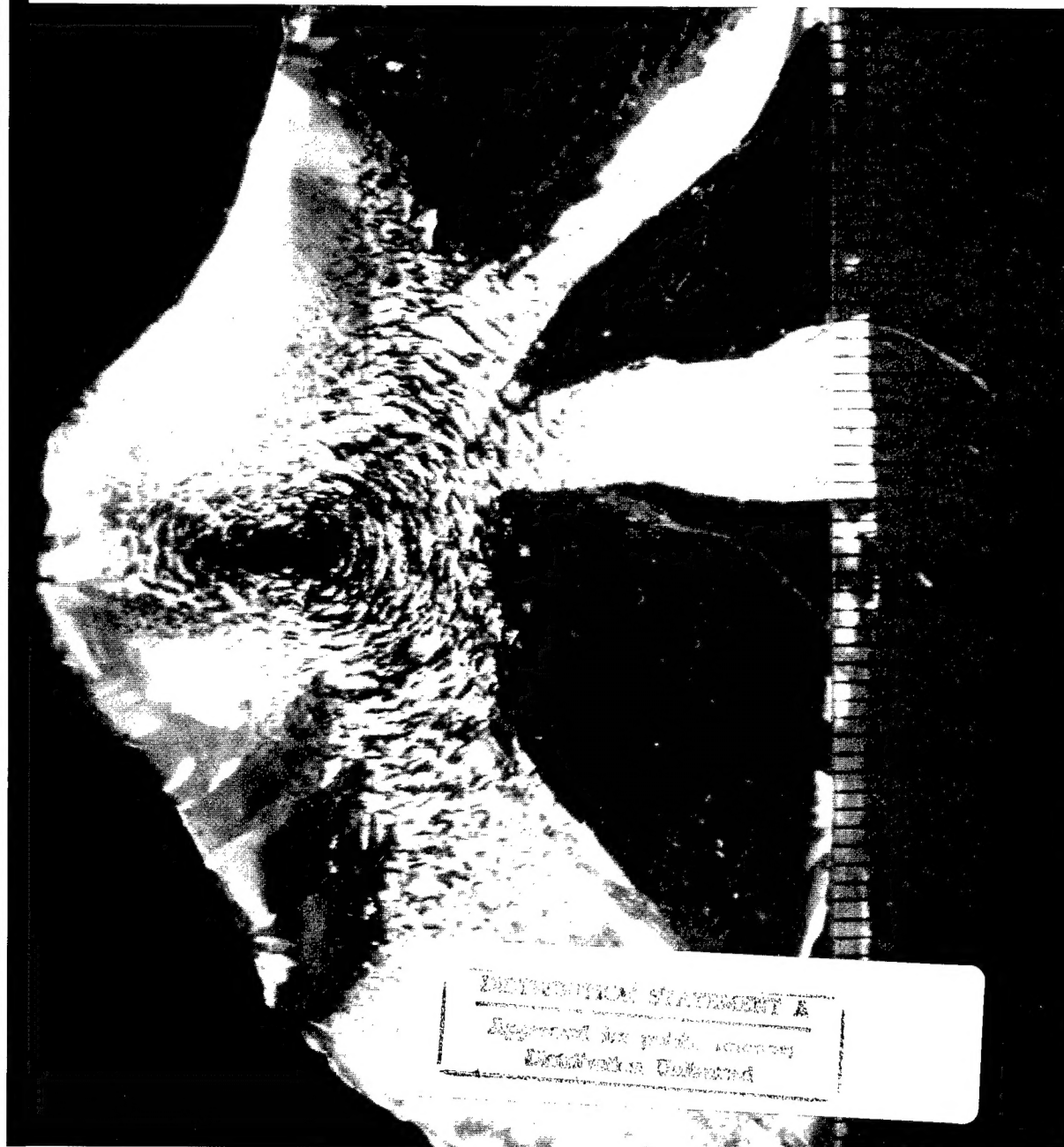




A Device for Mechanical Freeze-Thaw Conditioning of Alum Sludge

C. James Martel, Rosa T. Affleck and Melinda L. Yushak December 1996



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Abstract: This report contains the results of a study to develop a mechanical device for dewatering alum sludge by freeze-thaw. This proposed device is a combination of two conventional unit operations: a vacuum filter and a blast freezer. Bench-scale studies were conducted to evaluate this concept and develop preliminary design criteria. The results of filter leaf tests indicate that a suitable sludge layer could be collected on a cloth medium at a vacuum level of only 100 mm of Hg and a 5.0-minute filtration time. The volume of sludge was

reduced by 67%. The freezing tests indicated that low freezing rate and a high initial solids content had a tendency to produce large alum sludge particles. However, fast freezing rates could be achieved without reducing the effective grain size below that of a fine sand. Curing time had no effect on grain size. The electrical cost of freezing sludge with this device was estimated to be \$0.004/m³, which is not expensive in relation to the total cost of water treatment which is approximately \$0.25 to \$0.50/m³.

Cover: Cross-polarized photo of thin section of frozen alum sludge showing separation of solid particles and ice crystals.

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OFFICE OF THE CHIEF OF ENGINEERS

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PREFACE

This report was prepared by C. James Martel, Environmental Engineer, Rosa T. Affleck, Engineering Technician, and Melinda L. Yushak, Engineering Aid, Civil and Geotechnical Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory. This study was funded by Project 4A762784AT42, *Cold Regions Engineering Technology*, Work Package 211, *Installation Management in Cold Regions*, Work Unit CO-M20, *Innovative Methods for Wastewater Treatment and Sludge*.

Dr. P. Aarne Vesilind of Duke University and James R. DeWolfe of Gannett Fleming Engineers and Planners conducted a thorough technical review of this report.

Several people worked on this project over the last few years. Donna Thrasher and Beth Nadeau conducted most of the filter leaf tests. John Bayer developed a method to concentrate the sludge without using polymers or drying the sludge. Rosa Affleck conducted the grain size analysis and developed improved techniques for freezing, thawing and draining the sludge layers to enhance the reproducibility of the analysis. Melinda Yushak conducted most of the freezing tests and recorded the data.

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A Device for Mechanical Freeze-Thaw Conditioning of Alum Sludge

C. JAMES MARTEL, ROSA T. AFFLECK AND MELINDA L. YUSHAK

INTRODUCTION

Background

Disposal of alum sludge can be a major concern for water treatment plants, including those at military installations. The traditional practice of discharging the sludge directly into a nearby stream is becoming less acceptable because these discharges can violate state stream standards. Discharging the sludge into a sewer line is often used as an alternative. However, many plants are unable to use this alternative because they are not located near a sewer line or the treatment plant is unable to accept their discharge.

Because of the restrictions to stream and sewer discharges, many water treatment plants have turned to landfilling or land application as disposal methods. Most landfill regulations require a minimum of 20% solids and no evidence of free flowing liquid. Volume reduction prior to land application is often necessary to reduce transpor-

tation costs. Thickened alum sludge produced at the plant typically contains only 2% solids (98% water). Therefore, some method of dewatering is needed before alum sludge can be placed in a landfill or land applied.

Alum sludge is widely recognized as one of the most difficult sludges to dewater. About 40% of the water is chemically bound to the particles, which is difficult to remove by conventional methods such as vacuum filters, belt presses or centrifuges. With the aid of expensive polymers, these processes may be able to increase the total solids content up to 20%. However, this is not usually the case, and often the sludge is not dry enough to meet landfill requirements.

In contrast to conventional dewatering methods, freeze-thaw conditioning followed by gravity filtration can easily dewater this sludge without polymers. The process of freeze-thaw conditioning changes the sludge from a suspension of

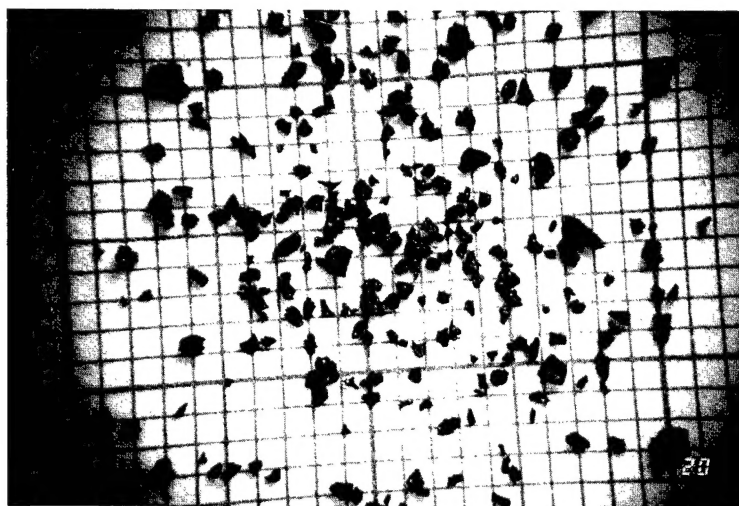


Figure 1. Sample of freeze-thaw-conditioned alum sludge on a 1.0-mm-square grid.

small particles to a granular material that resembles coffee grounds (see Fig. 1). These grains do not dissolve or suspend upon rewetting, even with vigorous agitation. This granular material can be easily handled and transported with conventional earth moving equipment. No other sludge conditioning or dewatering process can produce this dramatic transformation.

Because freeze-thaw conditioned sludge is in a granular form, land application becomes much more practical and economical. In areas where landfill costs are high, the land application option offers a significant savings in disposal costs. New Jersey American Water Company estimated that it could avoid a \$110/ton tipping fee if land application was possible (Brown et al. 1993). However, as pointed out by DeWolfe and Dempsey (1992), care must be taken to control a potential phosphorus deficiency in soils, which may impact plant growth.

The mechanism responsible for converting alum sludge into granular particles is the ice crystal formation process. It is well known that ice crystals form from water molecules only. All other substances including alum floc particles are pushed away from the growing ice crystal. This forces the floc particles to become consolidated at the boundaries between ice crystals. After freezing is complete, the sludge is no longer a suspension of fine floc particles but a matrix of ice crystals and consolidated floc particles or grains. When the ice crystals thaw, the grains remain consolidated and do not redissolve. These grains are large enough to easily settle by gravity in the clear meltwater. The sludge is dewatered by decanting or draining the meltwater.

In cold climates, freeze-thaw conditioning is easily accomplished during the winter months in outdoor freezing beds (Martel and Diener 1991). However, this technology is not usable at water treatment plants located in warm climates or at plants without the available land area. For these situations, a mechanical freezing device is needed. This report is the result of several years of study and experimentation in developing such a device.

Objectives

The objectives of this study are:

1. To develop a conceptual mechanical freeze-thaw conditioning device based on lessons learned from previous attempts.
2. To develop preliminary design criteria for the new device.

Scope

Objective 1 was accomplished by thoroughly reviewing the literature and evaluating past attempts at building a device. The main part of this study was devoted to developing the preliminary design criteria (Objective 2). These criteria were developed by bench scale studies conducted at CRREL in Hanover, New Hampshire.

HISTORY OF MECHANICAL FREEZE-THAW CONDITIONING

Literature review

Generally, mechanical sludge freezing devices can be categorized into bulk freezers, freeze crystallizers and layer freezers. A conceptual sketch of each freezer is shown in Figure 2.

Bulk freezers

The bulk freezer was the first mechanical device used to freeze sludge. It consists of a large container with refrigeration coils. Sludge is pumped into the tank where it remains until completely frozen. Thawing is also accomplished in the same container by reversing the refrigeration cycle. The meltwater is drained out of the container, leaving the granular sludge particles at the bottom. The container is then drained and emptied and the process is repeated. This method was used for several years at the Stocks Filtration Plant in Yorkshire, England (Benn and Doe 1969). It worked very well except that the tanks had a tendency to rupture after relatively few cycles due to the expansion force of ice (Farrell 1971).

A recent report by AWWA (1990) indicates that there are a few operational bulk freeze-thaw plants in Germany. The Wuppertal Municipal Works in West Germany reportedly uses a bulk freezing device similar to that described in Doe et al. (1969). Alum sludge containing approximately 2% solids is pumped into one of two sequentially operated freezing tanks. However, to avoid damaging the tank by the expansion of ice, only 40% of the tank contents are frozen.

Kawamura and Trussell (1991) report the use of freeze-thaw conditioning at the Kashiwai Water Purification Plant near Tokyo, Japan. Freeze-thaw is used because sludge from this plant is difficult to dewater by conventional methods. The sludge is gravity thickened and centrifuged prior to freezing. Twenty-five tanks are used to freeze and thaw the sludge. After thawing is complete, it is filtered by vertical belt presses to achieve 40–45% solids.

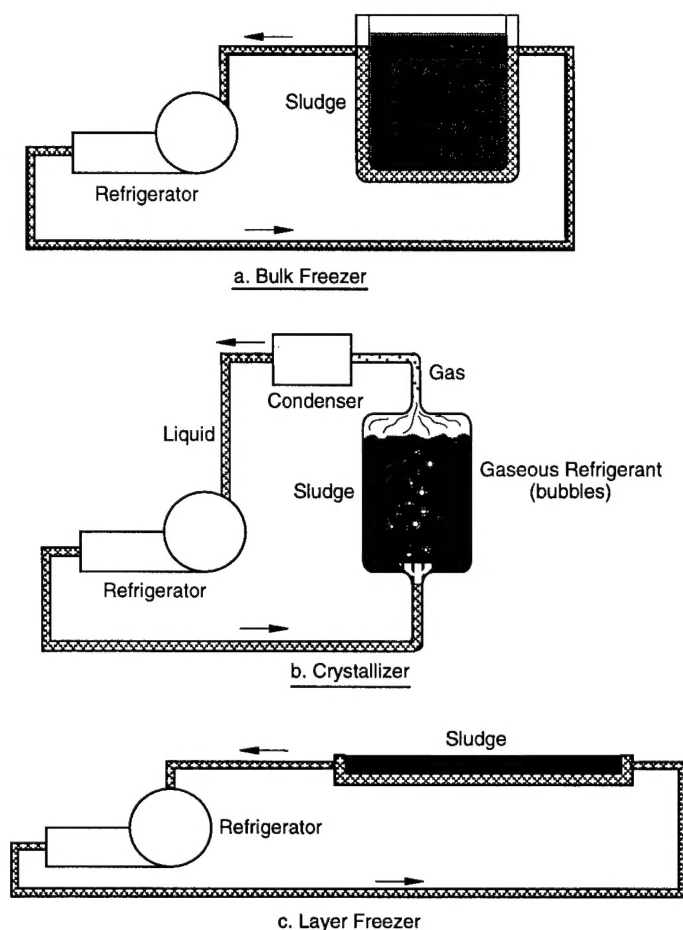


Figure 2. Conceptual sketches of three sludge freezing devices.

Crystallizers

Instead of freezing sludge into a solid mass, sludge can be frozen into a slurry of concentrated solids and pure ice crystals. This is done by mixing the sludge at a temperature below the freezing point. The slurry of ice crystals and solids is then sent to a separator where the ice crystals are washed with a portion of the melted ice crystals. This process is called freeze crystallization or freeze concentration. It has been used commercially for several years in concentrating fruit juices, milk, beer and other liquids for human consumption. It is also a proposed method for desalting seawater.

Randall et al. (1975) and Randall (1978) proposed freezing sludge by mixing it in a crystallizer with a refrigerant such as butane. They claim that this method results in better conditioning and supernatant quality than solid freezing. Also, they conclude that the cost of this process is more competitive with conventional dewatering processes because direct contact freezing is more

energy efficient than bulk freezing. However, this process has yet to receive widespread application because of explosion hazards and the difficulty in recovering all the butane.

Egan and Davis (1982) constructed a pilot-scale freeze crystallizer and tested its effectiveness on black liquor from the kraft pulp-manufacturing process. They choose this process over evaporation because it is less corrosive, produces less volatile compounds, and is potentially more energy efficient. Their tests demonstrated that a 15% black liquor can be concentrated to approximately 30% solids. In spite of this successful demonstration they were not able to find a commercially made, large freeze crystallizer. Because of this limitation, they concluded that the pulp and paper industry should not proceed any further, but instead keep abreast of new developments of this technology.

Knocke and Trahern (1989) investigated both bulk freezing and crystallization on conditioning chemical and biological sludges. They found that

the bulk freezing method was superior to freeze crystallization because it consistently improved the dewaterability of each sludge tested. In some cases, freeze crystallization actually worsened sludge dewaterability.

Layer freezers

As the name implies, a layer freezing device freezes sludge in thin layers or sheets. Freezing is usually accomplished on a refrigerated plate or belt. After freezing is complete, the layer is removed and broken into small pieces that are then thawed and drained. The layer freezing method is similar to bulk freezing in that sludge is frozen indirectly by a refrigerated surface. However, it avoids the mechanical stresses due to freezing by allowing expansion in the opposite direction from the freezing front. Also, it can freeze more sludge per unit energy input because freezing in thin layers is more efficient. The main disadvantage is the large surface area needed, which can translate into a large floor space requirement.

The first layer freezer for sludge was patented by Downes and Komline (no. 2,174,873) in 1939. Essentially it consists of a flat conveyor belt, a freezing chamber, and a thawing chamber. Digested sludge from a wastewater treatment plant is applied in a thin layer to the conveyor belt. The belt then transports the sludge into the freezing chamber where it is frozen. The conveyor belt continues through a heated section where the sludge is thawed and drained. The energy required for both freezing and thawing is derived from the anaerobic digestion process. No information was found in the literature on whether this device was ever tried full scale.

The Milwaukee Sewerage Commission (1971) evaluated two layer freezing methods for conditioning and dewatering waste activated sludge. The first method was a serpentine conveyor mounted in a cold air blast freezing unit. A series of pans were attached to the conveyor. Sludge was deposited in each pan before it entered the freezing unit. The pans entered at the top of the unit and traveled vertically downward in a serpentine fashion. This concept was not extensively evaluated because the pan conveyor was not commercially available and a need was anticipated for frequent defrosting. The second method involved the use of an endless steel belt that traveled over a brine cooled freezing section. This concept was judged to be more feasible because the belt freezing system was commercially available, and it had been used in other similar appli-

cations. Sludge containing 4% solids would be placed on top of the belt and frozen in 0.5-in. (1.3-cm) sheets. Studies indicated that it took 100 minutes to freeze the 1.3 cm of sludge. The Milwaukee Sewerage Commission's analysis concluded that energy costs and floor space requirements were appreciably higher for this dewatering method than a conventional vacuum filter. As a result, no further testing was conducted.

In 1973 and again in 1975, Carrier Corporation obtained patents (no. 3,745,782 and 3,880,756) on a "falling film" freezing device. This device consists of a pair of shell and tube heat exchangers which alternately serve as refrigerant evaporators and refrigerant condensers. The sludge is pumped to the top of the heat exchangers where it is distributed and allowed to flow down the interior of the heat exchange tubes. As it flows downward, the sludge is frozen in the form of hollow cylinders by the refrigerant evaporated on the exterior of the tubes. Sludge that is not frozen by the time it reaches the bottom of the tubes is collected and recirculated back to the top until the desired quantity of sludge is frozen. The refrigeration cycle is then reversed and the sludge is melted. The inventors claim that this process provides improved refrigeration cycle efficiency and avoids the structural failure problems associated with bulk freezing devices.

In 1976, the United Kingdom Atomic Energy Authority filed a patent (no. 1,459,175) for a drum freezer whereby sludge is sprayed on a refrigerated drum and allowed to freeze. Laboratory tests indicated that a 2.0-mm layer of alum sludge can be frozen within 20 seconds on a stainless steel drum cooled to -10°C . The frozen layer is removed by a rotating scraper and transferred to a thaw and settling tank. Supernatant is recirculated through a vapor condenser in the refrigeration circuit and the heated return flow is sprayed over the frozen sludge in the thaw and settling tank.

The Electric Power Research Institute (EPRI) conducted tests on a layer freezing device consisting of a vertical freezing plate. Sludge was sprayed on the top of the plate and allowed to flow downward by gravity. Any sludge that was not frozen was collected and recycled back to the top of the plate. Brown et al. (1993) found that this technique was only partially successful. The rejection of solids by the advancing freezing front caused a buildup of solids in the liquid phase. Eventually, the pump was incapacitated because it was unable to deliver the thickened sludge to

the freezing plate. Also, the sludge was too thick to flow down the freezing plate.

Conclusions from literature review

The layer freezing method appears to offer the best chance for commercializing the freeze-thaw conditioning process. It avoids the structural failure problem common to bulk freezers and the ice crystal/solid particle separation problem common to freeze crystallizers. The large surface area required by the layer freezing method is the main obstacle to overcome.

In spite of the high cost of freezing, we believe there is a niche for this process in conditioning difficult sludges like alum and other hydroxide sludges. Freeze-thaw conditioning is the only process that can transform these sludges from a thin pudding-like liquid into a granular material. Dewatering this granular material is a simple matter of decanting or filtering the meltwater. No polymers or further mechanical processing are needed. The granular nature of the final product has an added benefit in that it can greatly facilitate handling for both disposal and beneficial reuse. As a result, the overall cost of this method may be less than that for conventional methods when disposal costs are included.

PROPOSED FREEZE SEPARATOR CONCEPT

The proposed freeze-separator combines a vacuum drum filter with a horizontal belt freezer. A sketch of the proposed freeze-separator device is shown in Figure 3. This device is patented (no. 5,202,039).

The purpose of the drum filter is to remove most of the free water from the sludge before freezing. This will reduce the amount of sludge to

be frozen as well as the surface area requirement. Another important function of the drum filter is to attach the sludge to a flat surface in a uniform thin layer. A uniform layer is needed in order to ensure that the sludge is completely frozen by the time it exits the freezer.

Operation of the device begins at the vacuum drum filter. A rotating drum, immersed in a constantly replenished vat of sludge, filters free water through an attached cloth or metal belt. As the drum rotates, a layer of sludge builds up on the belt. The thickness of the sludge layer will depend on the filtration characteristics of the media, and the amount of vacuum applied. The filtrate is either returned to the head of the plant or used in the washing section. After the belt emerges from the vat, it enters the freezing chamber. The speed of the belt is controlled so that the sludge layer is completely frozen by the time it exits the chamber. The frozen sludge layer is then separated from the belt and discharged into a collection hopper. A heated roller may be needed to break the bond between the sludge and the belt. The frozen sludge layer is then thawed using the heat removed from the freezing chamber. Meltwater produced during this thawing operation is collected and mixed with the filtrate from the vacuum section. The remaining granular solids are then transported to a storage area, landfill, or land application site. Meanwhile the belt continues on through a washing section where any residual sludge particles are removed. The belt then reenters the vat and the cycle is repeated.

As mentioned earlier, the main advantage of this design over other freezing devices is that much of the water is removed before freezing. As a result, the energy required will be significantly reduced. Another advantage is that it is a contin-

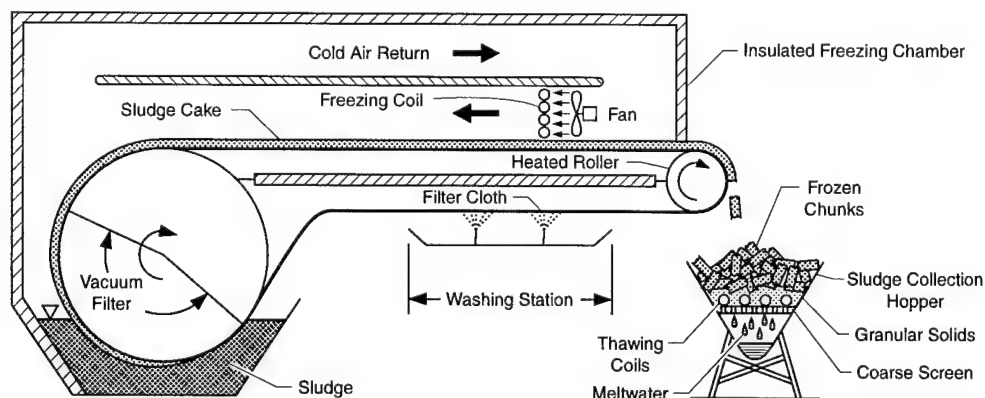


Figure 3. Conceptual sketch of freeze separator.

uous process. Both freezing and thawing can be conducted simultaneously. Also, the freezing and thawing process can be designed so that the heat removed during freezing can be used for thawing. Therefore, the cost of thawing the sludge should be negligible.

MATERIALS AND METHODS

Studies were conducted on the two main components of the freeze separator: the vacuum filter and the freezing chamber. The vacuum filter was evaluated using the filter leaf test. The freezing chamber was simulated by freezing layers of sludge in a coldroom.

The alum sludge used in this study was obtained from the water treatment plant in Lebanon, New Hampshire. This plant has a design flow of 15,000 m³/day. Treatment processes include rapid mixing, flocculation, sedimentation and sand filtration. Chemical additives include potassium permanganate, alum, powdered activated carbon and sodium bicarbonate. At present the sludge is discharged to a lagoon where the solids are left to accumulate and the water is allowed to percolate into the ground.

For these experiments, we took the settled sludge from the sedimentation basins. We tried to collect the thickest portions in order to reduce the number of containers. The total solids content of this sludge was typically 1 to 2%. The sludge was then transported to CRREL and stored in a coldroom at 0°C ± 2°C.

The characteristics of alum sludge from the Lebanon Water Treatment Plant were examined in a previous study (Martel 1988). This study found that the Lebanon sludge had a specific gravity of 1.005 and a volatile solids content of 52% (of total solids). This relatively high volatile solids content is due to

colloidal humic particles typically present in New England waters. The specific resistance to filtration before and after freeze-thaw was 4.8×10^9 and 6.0×10^8 s²/g at 38.1 cm of Hg, respectively. This reduction in specific resistance indicates an improvement in filterability due to freeze-thaw. Capillary section time (CST) tests showed similar results. CSTs before and after freeze-thaw were 32 and 6 seconds, respectively.

Filter leaf tests

The purpose of this test is to determine the optimum design criteria for the vacuum filter component of the freeze separator. These criteria are the type of filter cloth, vacuum level and filtration time. The filter leaf test apparatus was purchased from Komline Sanderson Engineering Corporation of Peapack, New Jersey. A filter leaf is essentially a 0.1-ft² (0.0093-m²) compartment of a vacuum filter made of polypropylene. It resembles a flattened funnel onto which a sample of the filter cloth is attached. The filter leaf is submerged in a container of sludge while a vacuum is applied at the other end. A schematic of a typical leaf test apparatus is shown in Figure 4.

Each filter leaf test proceeded as follows. We selected a filter cloth and attached it to the filter leaf test apparatus. The filter leaf was immersed in a 6-L container of alum sludge, which had a total solids content ranging from 0.34% to 2.08%. The desired vacuum was applied to the leaf and maintained throughout the filtration period. To simulate the circular motion of a filter cloth through a vat of sludge, the filter leaf was gently agitated by manually moving it up and down. Upon completion of the filtration period, the filter leaf was removed from the container and the sludge layer was allowed to "form-up" by maintaining vacuum for another 30 seconds. The thickness of the layer was measured with a machinist's ruler, and the cloth was removed from the filter leaf. The cloth and sludge were then weighed to obtain the weight of wet cake. The volume of filtrate was measured with a graduated cylinder and its turbidity was measured with a turbidimeter.

To observe the effect of freezing, the cloth and attached sludge layer were laid in an aluminum

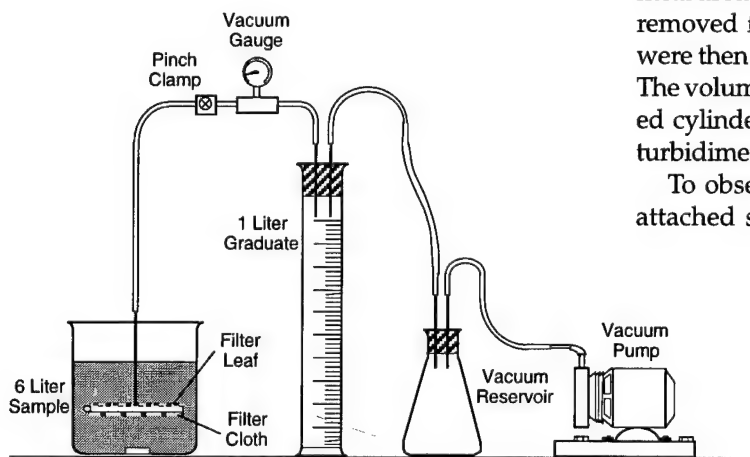


Figure 4. Filter leaf test apparatus.

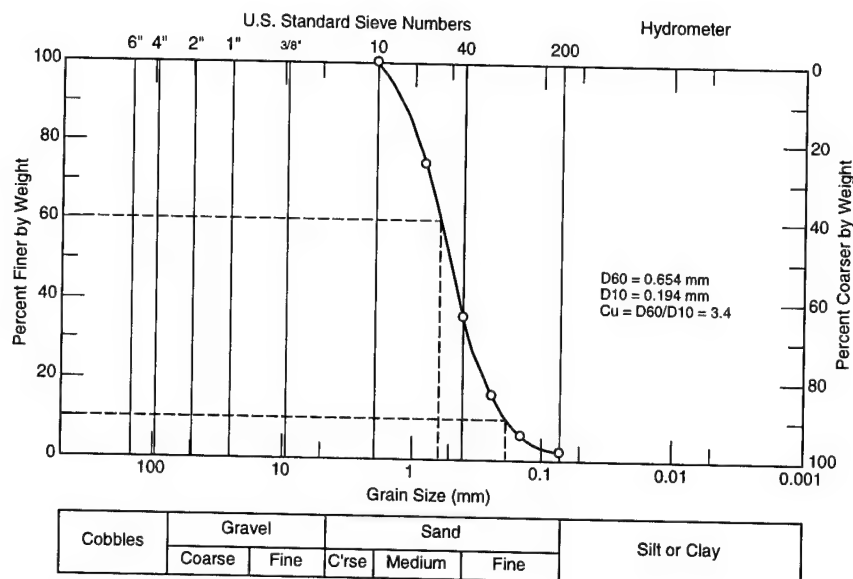


Figure 5. Size distribution curve for grains produced by freeze-thaw-conditioned alum sludge containing 6% total solids. The freezing temperature was -5°C .

pie plate, and placed in the coldroom at -20°C . When freezing was complete, the sludge layer was separated from the filter cloth by heating the underside of the cloth for a few seconds with a warm laboratory hot plate. The sludge layer was then thawed at room temperature. After thawing was complete, the meltwater was drained off and the remaining solids were weighed to determine a drained solids content. These solids were then dried in an 105°C oven for one hour to obtain the weight of dry cake. This completed a test. Altogether, 107 filter leaf tests were conducted in this study. Data obtained from these tests can be found in Appendix A.

Freezing tests

The purpose of the freezing test is to evaluate the effect of freezing rate, curing time and initial solids content on the quality of the product in terms of the effective grain size and uniformity coefficient. The freezing rate was varied by freezing the same quantity of sludge at four temperatures: -5° , -14° , -23° , and -30°C . The effect of curing time was determined by leaving the sludge in a coldroom for 1 and 24 hours after freezing was complete. The effect of initial solids content was tested by freezing sludge at three different total solids contents: 2%, 6%, and 12%. A 2% solids content was chosen because it represents a typical alum sludge after gravity thickening. A 6% solids content was chosen as representative of a typical alum sludge after vacuum filtration. A 12% solids content was chosen to simulate a typical alum

sludge after dewatering with a conventional belt press.

The effective grain size (D_{10}) is defined as the particle size corresponding to the 10% passing size from the grain size curve that is determined by a sieve analysis (see Fig. 5). It is well known that the permeability of soil or in this case, a granular sludge, will be controlled by this grain size. Since the meltwater must be drained after thawing, it is important that the final product have an effective grain size that is highly permeable. For practical purposes, this means that the effective grain size should be in the sand size range or higher. If the D_{10} value is in the silt or clay size range, the permeability of the product will be significantly reduced. According to the Unified Soil Classification System, the dividing line between sand and silt size particles is a D_{10} of 0.074 mm. This D_{10} value was used to determine practical limits on freezing rate, curing time and initial solids content.

The uniformity coefficient (C_u) is another common soil property that we applied to this study. It is defined as the ratio between the 60% passing size and the 10% passing size (D_{60}/D_{10}). This ratio provides a comparative indication of the range of particle sizes. A granular material is considered to have a uniform grain size distribution if the C_u is less than 5.

Prior to conducting the freezing tests, we prepared three batches of sludge containing 2%, 6%, and 12% total solids. The 2% batch was obtained by allowing the sludge to settle for several days



Figure 6. Nest of sieves (no. 30, 50 and 100) used to concentrate alum sludge to 6% and 12% total solids.

and decanting the supernatant. To produce the 6 and 12% batches, we had to filter the sludge through a series of large sieves (see Fig. 6). These sieves rested on a rectangular container that collected the filtrate as well as any particles passing the sieves. After pouring sludge onto the sieves, we covered them with plastic wrap, a board, and various weights. The purpose of the plastic wrap was to prevent drying, and the purpose of the board and weights was to increase pressure on the sludge. We monitored the filtration process by periodically analyzing the total solids content. After the desired total solids content was achieved, the sludge was removed from each sieve, mixed together, and stored in a container. The particles in the filtrate were also added to the container after they were separated from the water by a series of steps, including filtration through no. 200 and 400 sieves, decanting, and evaporation (without allowing the sludge particles to become dry). As a result none of the solids were lost and the batch contained the full spectrum of sludge particle sizes.

To simulate layer freezing, the sludge was frozen in shallow trays made from clear plastic acrylic. This material was chosen because it allowed a visual observation of the underside of the sludge layer. Each tray is designed to freeze a layer 360 mm in diameter and 6 mm thick. A thickness of 6 mm was chosen based on the results

of the filter leaf tests, which demonstrated that a sludge layer of this thickness was possible. Three trays were used in each test.

For thin layers, the freezing time can be predicted from the equation (Vesilind 1990)

$$t_f = \frac{\rho_f L \epsilon}{h_c (T_f - T_{af})} \quad (1)$$

where t_f = the freezing time (hours)

ρ_f = the density of ice (917 kg/m³)

L = the latent heat of fusion (93 W-h/kg)

ϵ = the thickness of the sludge layer (0.006 m)

T_f = the freezing point of sludge (0°C)

T_{af} = the average air temperature in the coldroom (°C)

h_c = the average convection coefficient (W/m²-°C).

This equation assumes that the sludge is already at the freezing point before entering the coldroom and that freezing occurs from the top surface downward. We attempted to comply with these assumptions by precooling the sludge in a 0°C coldroom and by insulating the bottom of the trays. The only unknown in eq 1 is the value of the convection coefficient, h_c . Based on a separate study (see App. B), the average convection coefficient in the coldroom was calculated to be 23.1 W/m²-°C.

The actual freezing time was determined by observing the bottom of the sludge layer through the transparent freezing tray. We knew that a sludge layer was completely frozen when it became transparent due to presence of clear ice crystals.

The difference between the actual and predicted freezing times was less than one minute on average. However, the standard deviation was ± 32.3 minutes and differences ranged from -48.3 to 88.7 minutes (see App. C). The reason for these large differences were due, at least in part, to slight differences in mass content. Under the same conditions, a tray containing a greater mass of sludge took longer to freeze than one with less. When adjusted for mass, differences in freezing rates were reduced but not completely eliminated. For the purpose of this experiment, an accurate prediction was not necessary. We used the actual freezing times to calculate all freezing rates.

The procedure used to freeze sludge in the trays is as follows:

1. The three trays and sludge were placed in a



Figure 7. Placing a tray containing alum sludge in a coldroom.

- 0°C coldroom until they reached ambient temperature. The purpose of this step is to start each test at the same initial temperature condition.
2. The trays and the sludge were transferred to a coldroom, which was set at the desired freezing temperature. The trays were placed on a level, insulated table (see Fig. 7). Sludge was poured into each tray and spread to a uniform 6-mm depth with a plastic scraper.
 3. For the freezing rate and initial solids content tests, the trays were removed as soon as the sludge layer was frozen (see Fig. 8). For the curing time test, only one of the trays was removed and the remaining two trays were allowed to cure. After removing the trays from the coldroom, we carried them to a laboratory where they were weighed and allowed to thaw at room temperature. Drainage was accomplished by placing each tray at a slight angle so that meltwater could drain away without dislocating the solids. The trays were left in the laboratory over-

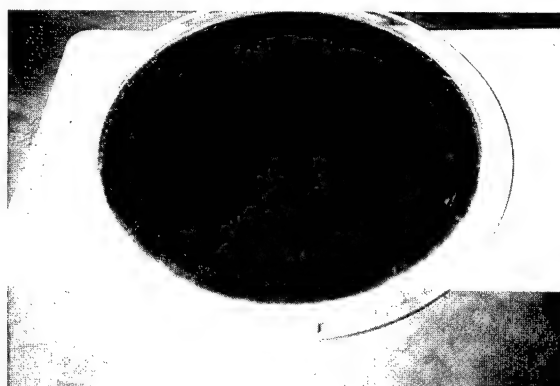


Figure 8. Tray of frozen alum sludge.

- night in order to allow the solids to dry out.
4. In the morning, each tray was placed in an oven at 104°C for one hour to complete the drying process. The trays were then removed, allowed to cool for 15-minutes, and weighed to obtain the dry weight.

A grain size analysis was performed on the solids from each tray with U. S. Standard 8-in.-diam. sieves 10, 20, 40, 60, 100, and 200. The sieves were shaken for 10 minutes using a machine shaker. The amount of solids retained on each tray were then weighed and recorded. Grain size distribution curves were then plotted to determine D₁₀ and C_u. Data from the layer freezing tests are shown in Appendix C.

RESULTS

Filter leaf tests

Cloth selection

Because of the large number of filter cloths available, we decided to base our initial selection on the ones most likely to produce a clear filtrate.

Table 1. Average turbidity of filtrate from selected filter cloths.

Cloth number*	Material	Weave	Porosity		Avg. filtrate turbidity (NTU)
			ft ³ /min	(m ³ /min)	
515	Nylon	Sateen	2-3	(0.06-0.08)	8.9
210	Dacron	Crowfoot	5-2	(0.06-0.14)	14.7
2019	Polypropylene	Twill	1-2	(0.03-0.06)	17.3
208	Dacron	Crowfoot	14	(0.40)	21.3
201	Dacron	Crowfoot 3 × 1	37	(1.05)	21.7
2015	Polypropylene	Twill 2 × 2	18	(0.51)	26.0
525	Nylon	Sateen	5	(0.14)	31.0
507	Nylon	Sateen	25	(0.71)	40.0
2038	Polypropylene	Twill	8	(0.23)	51.0
2016	Polypropylene	Twill	3	(0.08)	62.3
2025	Polypropylene	Twill 2 × 2	25	(0.71)	66.7

*According to Komline Sanderson Engineering Corp., Peapack, New Jersey.

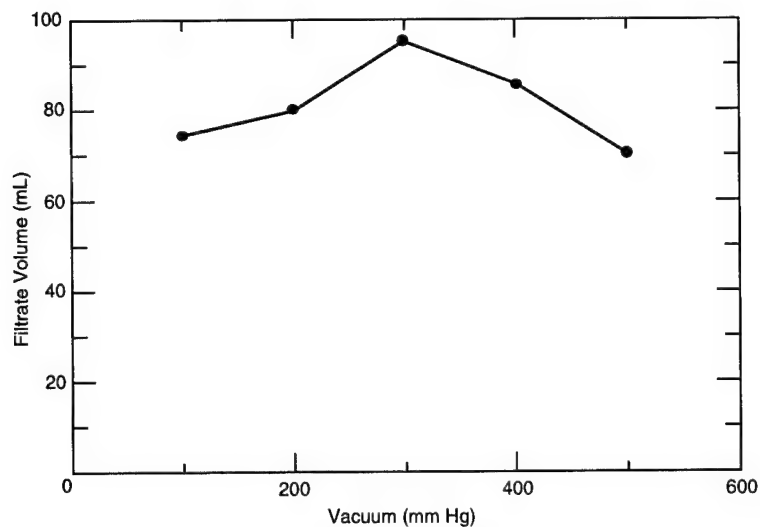


Figure 9. Effect of vacuum level on the volume of filtrate produced by cloth 515 after a 2.0-minute filtration time.

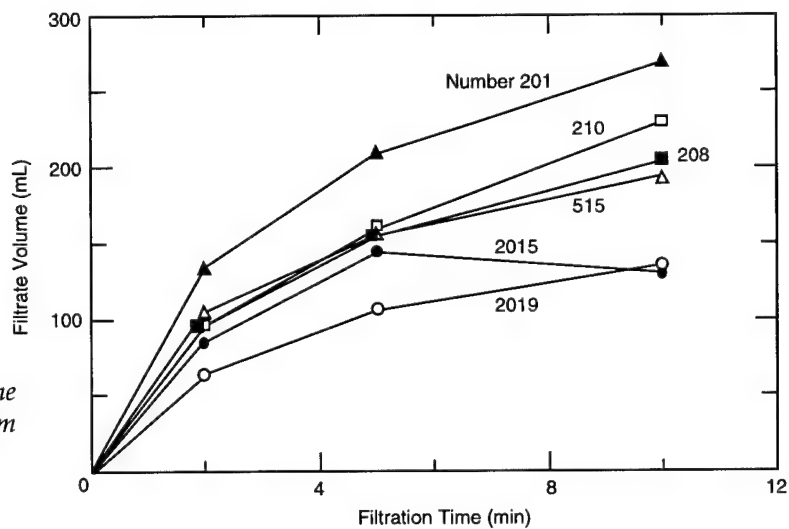


Figure 10. Effect of filtration time on the volume of filtrate produced at 100-mm Hg vacuum.

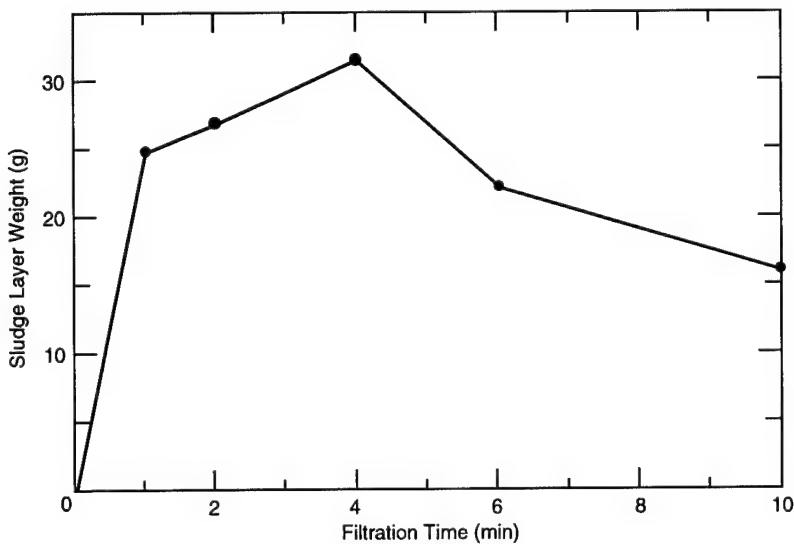


Figure 11. Effect of filtration time on the weight of the sludge layer accumulated on cloth 2019 at 100 mm of Hg vacuum in alum sludge containing 1.85% total solids.

A clear filtrate is important because it indicates a good solids capture by the filter cloth and a low solids loading in the filtrate return flow to the plant. The clarity of the filtrate was measured with a turbidimeter. We selected eleven cloths based on their porosity values. Those with a low porosity were assumed to have a greater potential for producing a clearer filtrate.

Each filter cloth was tested at a vacuum pressure of 100 mm of Hg, and filtration times of 2, 5, and 10 minutes. As shown in Table 1, the clearest filtrate was produced by cloth 515, although cloths 201, 208, 210, 2015 and 2019 all had turbidities less than 30 NTU, which is reasonably clear. As expected, the clearer filtrates were produced by the cloths with lower porosities. The type of material or the weave of the cloth did not seem to make a difference.

Vacuum level

To conserve energy, the vacuum level applied should only be high enough to form a sludge layer on the filter cloth while significantly reducing the volume of sludge to be frozen. To determine this optimum level, filter leaf tests were conducted with cloth 515 at 100, 200, 300, 400, and 500 mm of Hg. The total solids content in the alum sludge was 1.14%, and the filtration time was set at 2.0 minutes. The results of these tests indicate that increasing the vacuum level did not significantly increase the volume of filtrate (see Fig. 9). This behavior is indicative of a compressible sludge layer where particles are drawn into a more compact arrangement by the increased vacuum level. The only benefit from a higher vacuum level appears to be a more rapid rate of solids accumulation on the media surface.

Filtration time

The filtration time is important because it determines the drum speed at a fixed submergence level. For practical purposes, it should be long enough to coat the filter cloth with a thick layer of sludge while continuously removing filtrate. Six different filter cloths were tested (see Fig. 10) at three filtration times: 2, 5, and 10 minutes. Five of the filter cloths produced similar results in that the volume of filtrate increased as the filtration time increased. The only exception was cloth 2015, which showed a decrease in filtrate volume after 5 minutes, presumably because of a more rapid solids buildup due to a higher initial solids content. For the same reason we suspect that cloth 2019 produced low filtrate volumes because the sludge

used in these tests had almost twice the initial solids content.

In addition to removing water in the form of filtrate, the vacuum filter must also accumulate and retain a uniform layer of sludge on the filter cloth for subsequent freezing. Tests conducted with cloth 2019 (see Fig. 11) indicate that the weight of the sludge layer increased as the filtration time was increased from 0 to 4 minutes. Longer filtration times caused a decrease in the sludge layer. The reason for this decrease is not clear. Perhaps some of the attached solids were released as the layer compressed due to prolonged filtration.

Characteristics of sludge layer

The thickness of the sludge layer on the filter cloth ranged from 1 to 7 mm. The total solids content in these layers ranged from 1.0% to 6.9%. The main determining factor for layer thickness seems to be the solids content in the initial sludge. A high solids content in the sludge translated into a layer of greater thickness and higher solids content.

After the sludge layer was frozen, it was removed from the filter cloth as described earlier. The layer was mostly opaque except in the areas where transparent ice crystals penetrated the sludge layer from top to bottom. As each sludge cake thawed, the clear meltwater quickly drained away. When thawing and drainage were complete, all that remained was a small deposit of granular solids. The average solids content of this deposit was 11.8%. If left to dry overnight, the solids content reached 70% or more.

One of the most important operational concerns when using vacuum filtration is the condition of the filter cloth after several cycles. Based on visual observations, the filter cloth separated very cleanly from the frozen sludge layer as long as the layer was completely frozen (see Fig. 12). To evalu-



Figure 12. Cloth 2019 after removal of sludge layer. Note clean separation of sludge layer from cloth.

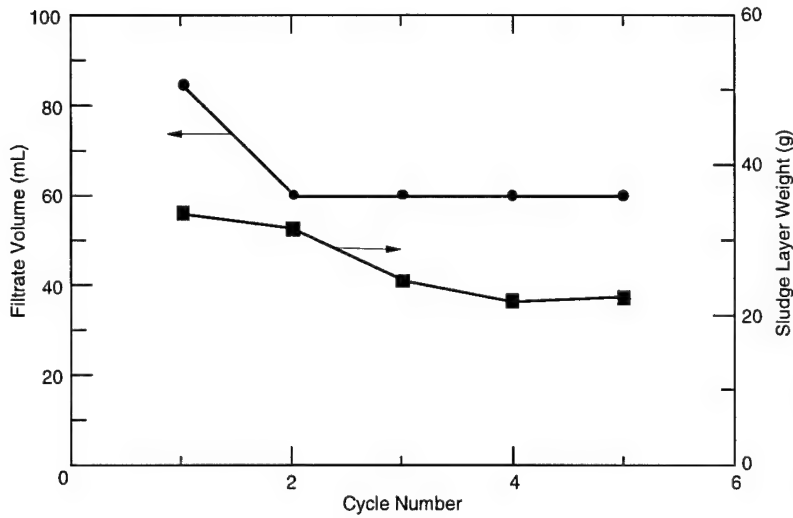


Figure 13. Effect of repeated use of cloth 2019 at 100 mm of Hg vacuum and a 5.0-minute filtration time in alum sludge containing 1.0% solids.

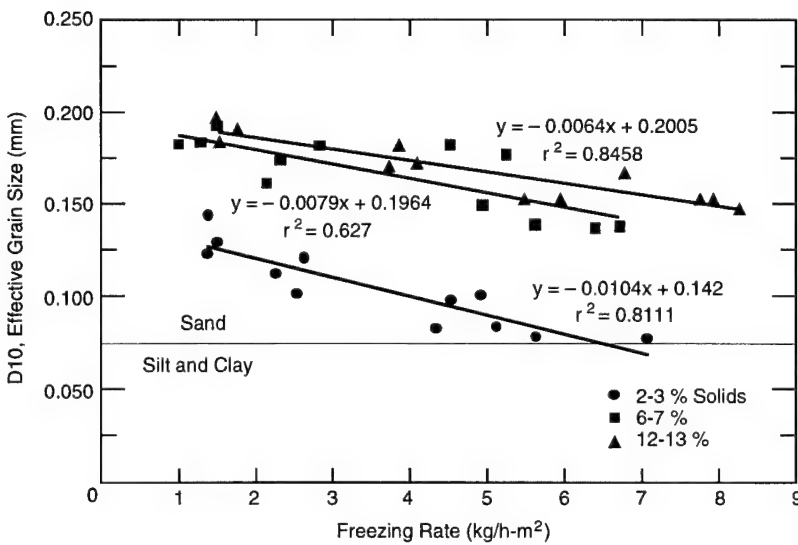


Figure 14. Effect of freezing rate of effective grain size of freeze-thaw-conditioned alum sludge.

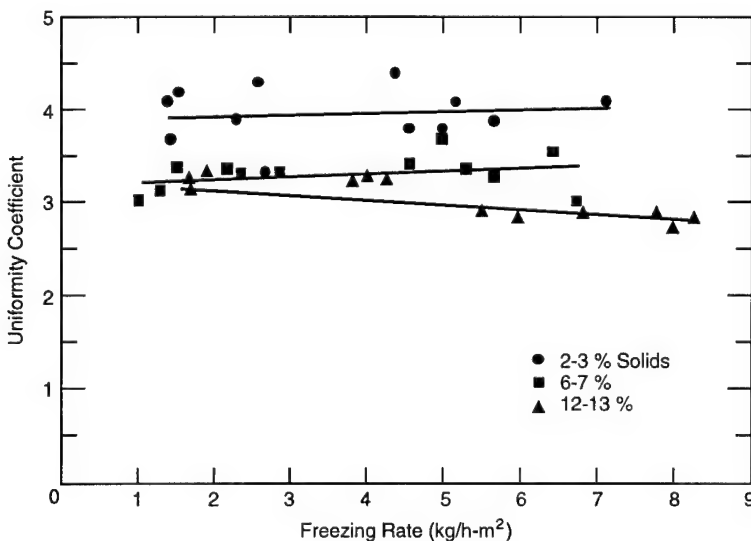


Figure 15. Effect of freezing rate on uniformity coefficient.

ate this observation, a series of five leaf tests were conducted with cloth 2019 at 100 mm of vacuum and a 5-minute filtration time. The sludge layer was completely frozen and the filter cloth was not washed between cycles. Results of this test indicate that the filtrate volume dropped from 85 to 60 mL after the second cycle but then stabilized at a constant 60 mL for the remaining three cycles (see Fig. 13). Concomitantly, the sludge layer weight gradually decreased during the first four cycles and then increased slightly during the fifth cycle. These results suggest that the filter cloth had reached an operational steady state after the first four cycles so the wash cycle could be eliminated.

Freezing test

The results of the freezing tests show that both the rate of freezing and the initial solids content have a significant effect on particle size. As shown in Figure 14, the effective grain sizes (D10) for all three sludges were in the sand size range. However, D10 decreased as the freezing rate increased. Also, the sludges that contained a higher initial solids content produced larger grains. The largest grains were produced by the sludge containing 12–13% solids. The grains produced by the sludge containing 2–3% solids were significantly smaller.

Based on the data shown in Figure 14, the effective grain size (D10) of frozen 2–3% sludge entered the silt and clay particle size range at a freezing rate of 6.6 kg/h-m². For the 6–7% and the 12–13% sludges, the crossover points are 15.5 and 19.8 kg/h-m² respectively.

Table 2. Data on effect of curing time on effective grain size (D10) and uniformity coefficient (C_u) of freeze-thaw conditioned alum sludge containing 2–3% solids.

Test number	Curing time (hr)	Effective grain size (D10) (mm)	Uniformity coefficient (C_u)
A3	24	0.13	3.9
B1	0	0.13	3.5
B2	1	0.13	4.0
B3	24	0.14	3.9
C1	0	0.13	4.0
C2	1	0.14	3.2
C3	24	0.12	4.3
D1	0	0.13	3.4
D2	1	0.11	3.7
D3	24	0.13	3.5

Freezing rate appeared to have little effect on the uniformity coefficient (see Fig. 15). However, the plot suggests that the uniformity coefficient decreases with increasing initial solids content. The average uniformity coefficients are 4.0, 3.3, and 3.0 respectively for the 2–3%, 6–7%, and 12–13% solids sludges, respectively. A statistical analysis of this data indicates that these differences are significant at the 95% level. This means that a more uniform grain size can be expected from freeze-thaw conditioned sludges containing a greater initial solids content. The reason for this phenomenon is not clear but perhaps there is less opportunity for particle movement away from the freezing front in sludges with higher initial solids because of the close intraparticle proximity. As a result there would be fewer opportunities to form various particle size combinations.

The curing time tests were conducted with alum sludge containing 2–3% solids. After freezing was complete, sludge samples were cured at –4°C for periods of 1 and 24 hours. As shown in Table 2, curing times of 1 and 24 hours appeared to have no effect on the grain size or uniformity coefficient of freeze-thaw conditioned alum sludge containing 2–3% solids. Neither the 6–7% or the 12–13% solids sludges were tested because of the apparent lack of any effect on the sludge with the 2–3% solids.

DISCUSSION

The results of the filter leaf tests show that vacuum filtration can remove most of the water from the sludge and, at the same time, produce a uniform thin layer for freezing. The optimum operational conditions for the vacuum filter are a vacuum level of 100 mm of Hg and a 5.0-minute filtration time. Generally, vacuum filtration increased the total solids content of alum sludge from 2% to approximately 6%. This represents a 67% reduction in the volume of sludge to be frozen. After freezing, thawing, and draining of meltwater, the remaining granular material contained approximately 12% solids. Although 12% solids is relatively low, further dewatering will rapidly occur by air drying. Our tests show that the sand size particles dried to a solids content of 70% or more within a few hours.

Several filter cloths were able to produce a clear filtrate even after repeated use. Therefore, selection of the right filter cloth for this application may depend more on its durability to withstand several freeze-thaw cycles than its ability to produce a

clear filtrate. Also, we were surprised by the relative cleanliness of the filter cloths after each use. This observation and the tests we conducted suggest that washing requirements would be minimal, but a longer term study is needed to confirm this finding.

The freezing tests indicate that the initial solids content is an important parameter in determining the effective grain size. Sludges that contained a greater solids content had larger effective grain sizes. For example, at a freezing rate of 6 kg/h-m^2 the effective grain sizes were 0.16, 0.15, and 0.08 mm for the sludges containing the 12–13%, 6–7%, and 2–3% solids, respectively. The reason for the larger grain size in the thicker freeze-thaw conditioned sludges may be the availability of more solids to fill the space between crystal boundaries. An important conclusion from this finding is that filtering alum sludge before freezing not only reduces the amount of sludge to be frozen, but it increases the grain size of the product. Therefore it may be more advantageous to use a belt press rather than a vacuum filter prior to freezing. As mentioned previously, a vacuum filter will dewater alum sludge to 6% solids, while a belt presses can typically dewater alum sludge to 12% solids.

The estimated size of the surface area needed for the horizontal belt freezer serving a $3,785 \text{ m}^3/\text{day}$ (1,000,000 gal./day) plant is 10.2 m^2 . This estimate is based on the following assumptions: 1) the sludge production rate is 1% of the water processed (Sanks 1978) and the specific gravity is approximately equal to water, i.e. 1.0, 2) the vacuum filter reduces the volume of sludge by 67%, 3) the freezing rate is 15.5 kg/h-m^2 , and 4) the operational period is 8 hours/day. If the belt is 1.2 m wide, the length of the freezing chamber would be 8.5 m. This is about the same size as the blast freezers used by the food industry. A greater capacity could be achieved by operating for longer periods. For example, the unit could handle the sludge produced by a $11,355 \text{ m}^3/\text{day}$ plant if it were operated 24 hours/day.

If a belt press were used instead of a vacuum filter, the surface area of the horizontal belt freezer could be reduced from 10.2 m^2 to 4.0 m^2 . This reduction is based on the assumption that the belt press will reduce the sludge volume by 83% and the freezing rate can be increased to 19.8 kg/h-m^2 , as indicated by our tests. This configuration would be particularly beneficial to large plants where floor space is limited.

One of the major concerns about the use of freeze-thaw conditioning is the energy required

by the phase change operation. Theoretically it takes 93 watt-hours to convert 1 kilogram of water (or sludge) to ice. Also, it takes 1.16 W-h/C° to cool the liquid sludge to the freezing point and 0.58 W-h/C° to cool the frozen sludge below the freezing point. If we assume an initial temperature of 10°C and a final temperature of -2°C , the energy required to freeze one metric ton (1,000 kg) of sludge is 105.8 kW-h. Assuming 50% losses due to air infiltration, the estimated energy required is $158.6 \text{ kW-h/metric ton}$. If the electrical cost is assumed to be $\$0.07/\text{kilowatt-hour}$, the cost of freezing one metric ton of sludge is $\$11.10$. In terms of water used, the cost is $\$0.004/\text{m}^3$ since it takes approximately 3000 m^3 of treated water to produce one metric ton of sludge. This is a relatively small cost compared to the total cost of water treatment which typically ranges from $\$0.25$ to $\$0.50/\text{m}^3$.

CONCLUSIONS

The bench-scale tests conducted in this study indicate that the proposed freeze separator concept is technically and economically feasible. The filter leaf tests show that the vacuum filter should be able to reduce the sludge volume by at least one-third. The optimum operational vacuum was 100 mm of Hg and the filtration time was 5.0 minutes. Any low porosity cloth appears to be suitable from a filtrate quality point of view. However, the durability of these filter cloths after many freeze-thaw cycles is still unknown.

The results of the freezing studies show that both freezing rate and initial solids content will affect the grain size of the freeze-thaw conditioned sludge. In general, faster freezing rates will cause a decrease in grain size. Conversely, sludges containing a greater initial solids content will produce larger grains. The maximum freezing rate for the proposed freeze separator is projected to be 15.5 kg/h-m^2 . Faster freezing will reduce the effective grain size below that of fine sand. This could result in a decrease in the hydraulic conductivity of the granular material, which is important for removing meltwater.

Based on the excellent results obtained from freezing alum sludge containing 12–13% solids, we concluded that it may be more effective to use a belt filter rather than a vacuum filter prior to freezing. A belt press would remove up to 50% more water from the sludge and thus reduce the cost of freezing. Also, the freezing rate could be increased to 19.8 kg/h-m^2 .

Curing time had no significant effect on grain

size. Therefore, there is no need to keep the sludge frozen beyond the freezing time, so that the thawing process can begin as soon as the sludge exits the freezer.

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**APPENDIX A: FILTER LEAF TEST DATA FOR
LEBANON, NEW HAMPSHIRE, WATER PLANT SLUDGE.**

Test number	Media number	Initial solids (%)	Filtration time (min)	Vacuum pressure (mm Hg)	Filtrate volume (mL)	Filtrate clarity (NTU)	Cake thickness (mm)	Weight		Wet cake solids (%)	Drained solids (%)
								Wet cake (g)	Dry cake (g)		
1	2013										
2	2019										
3	2006		1.5		3						
4	2016		1.5		190		3				
5	2038		1.5		375		3				
6	525		1.5		1						
7	525		1.5		75		1				
8	525		2.0		90		1				
9	515		2.0		60		1				
10	515		5.0		135		3				
11	2019		5.0		130		3				
12	210		2.0		90		1				
13	210		5.0		135		3				
14	531		2.0		100		1				
15	531		5.0		165		1				
16	515	1.14	2.0	500	70		1	19.554	1.111	5.7	
17	515	1.14	5.0	500	100		1	29.349	1.299	4.4	
18	515	1.14	7.0	500	185		1	22.707	1.226	5.4	
19	515	1.14	7.0	500	230		1	8.812	0.558	6.3	
20	525	1.14	2.0	500	80		3	22.655	1.027	4.5	
21	515	1.14	7.0	500	110		3	32.203	1.475	4.6	
22	525	1.14	5.0	500	115		3	19.693	1.081	5.5	
23	525	1.14	7.0	500	140		3	12.678	0.875	6.9	
24	515	1.14	2.0	100	75	5.5	1				
25	515	1.14	2.0	200	80	5.4	1				
26	515	1.14	2.0	300	95	15.0	1				
27	515	1.14	2.0	400	85	12.0	1				
28	515	1.14	2.0	400	100	8.0	1				
29	515	1.14	2.0	500	70	8.0	1				
30	515	1.14	5.0	100	130	2.5	1				
31	507	1.14	2.0	100	115	55.0	1				
32	507	1.14	2.0	200	135	55.0	1				
33	507	1.14	2.0	300	130	55.0	1				
34	507	1.14	2.0	400	125	40.0	1				
35	507	1.14	2.0	500	125	35.0	1				
36	210	0.41	2.0	100	95	25.0	1	5.055	0.232	4.6	
37	210	0.41	5.0	100	160	15.0	1	12.282	0.420	3.4	
38	210	0.41	10.0	100	230	4.0	1	13.532	0.413	3.1	
39	208	0.41	2.0	100	95	35.0	1	10.043	0.359	3.6	
40	208	0.41	5.0	100	155	25.0	1	13.710	0.454	3.3	
41	208	0.41	10.0	100	205	4.0	1	10.476	0.368	3.5	
42	201	0.34	2.0	100	135	35.0	1	5.012	0.209	4.2	
43	201	0.34	5.0	100	210	15.0	1	4.652	0.201	4.3	
44	201	0.34	10.0	100	270	15.0	1	5.024	0.251	5.0	
45	515	0.34	2.0	100	105	10.0	1	5.026	0.229	4.6	
46	515	0.34	5.0	100	155	8.5	1	10.428	0.403	3.9	
47	515	0.34	10.0	100	195	8.2	1	8.348	0.371	4.4	
48	525	0.47	2.0	100	120	50.0	1	6.551	0.306	4.7	
49	525	0.47	5.0	100	215	25.0	3	16.383	0.530	3.2	
50	525	0.47	10.0	100	215	18.0	3	20.562	0.628	3.1	
51	507	0.47	2.0	100	90	55.0	1	9.048	0.367	4.1	
52	507	0.47	5.0	100	155	30.0	1	10.286	0.419	4.1	
53	507	0.47	10.0	100	185	35.0	1	11.900	0.478	4.0	
54	2019	0.70	2.0	100	65	20.0	1	9.580	0.289	3.0	
55	2019	0.70	5.0	100	105	15.0	3	21.458	0.584	2.7	
56	2019	0.70	10.0	100	135	17.0	3	24.543	0.630	2.6	
57	2016	0.70	2.0	100	75	65.0	3	15.745	0.416	2.6	
58	2016	0.70	5.0	100	120	60.0	1	16.190	0.341	2.1	
59	2016	0.70	10.0	100		63.0	1	12.523	0.379	3.0	

Test number	Media number	Initial solids (%)	Filtration time (min)	Vacuum pressure (mm Hg)	Filtrate volume (mL)	Filtrate clarity (NTU)	Cake thickness (mm)	Weight		Wet cake solids (%)	Drained solids (%)
								Wet cake (g)	Dry cake (g)		
60	2038	0.82	2.0	100	45	65.0	1	8.717	0.203	2.3	
61	2038	0.82	5.0	100	165	35.0	3	18.179	0.404	2.2	
62	2038	0.82	10.0	100	65	53.0	1	9.899	0.168	1.7	
63	2015	0.82	2.0	100	85	33.0	3	32.315	0.687	2.1	
64	2015	0.82	5.0	100	145	25.0	1	24.276	0.602	2.5	
65	2015	0.82	10.0	100	130	20.0	1	21.738	0.629	2.9	
66	2025	0.82	2.0	100	85	50.0	1	15.199	0.052	0.3	
67	2025	0.82	5.0	100	105	85.0	1	21.906	0.653	3.0	
68	2025	0.82	10.0	100	130	65.0	1	21.225	0.387	2.1	
69	2019	0.98	5.0	100	85	15.0	3	33.807	1.042	3.1	
70	2019	0.98	5.0	100	60	13.0	3	31.595	0.958	3.0	
71	2019	0.98	5.0	100	60	18.0	1	24.436	0.804	3.3	
72	2019	0.98	5.0	100	60	20.0	1	21.762	0.833	3.8	
73	2019	0.98	5.0	100	60	18.0	1	22.315	0.768	3.4	
74	2015	1.10	5.0	100	85	20.0	3	41.366	1.177	2.8	
75	2015	1.10	5.0	100	85	17.0	3	38.858	1.117	2.9	
76	2015	1.10	5.0	100	85	10.0	3	44.343	1.126	2.5	
77	2015	1.10	5.0	100	80	22.0	3	34.715	1.030	3.0	
78	2015	0.89	5.0	100	150	5.0	3	31.473	0.797	2.5	
79	2015	0.89	5.0	100	140	5.3	3	31.822	0.891	2.8	
80	2015	0.89	5.0	100	130	9.5	3	35.365	0.953	2.7	
81	2015	0.89	5.0	100	130	9.5	3	37.791	0.993	2.6	
82	2015	0.60	5.0	100	170	3.5	1	23.424	0.235	1.0	
83	2015	0.60	5.0	100	200	5.0	1	12.919	0.335	2.6	
84	2015	0.60	5.0	100	175	15.0	1	12.717	0.202	1.6	
85	515	0.60	5.0	100	125	6.5	1	14.713	0.565	3.8	
86	515	0.60	5.0	100	105	7.0	1	11.626	0.437	3.8	
87	2019	1.85	1.0	100	25	25.0	3	24.848	0.887	3.6	
88	2019	1.85	2.0	100	30	35.0	3	26.822	1.293	4.8	
89	2019	1.85	4.0	100	35	20.0	4	31.493	1.055	3.4	11.4
90	2019	1.85	6.0	100	50	40.0	4	22.191	0.945	4.3	12.3
91	2019	1.85	10.0	100	50	30.0	3	15.830	0.732	4.6	11.7
92	210	2.08	1.0	100	15	30.0	2	13.152	0.545	4.1	11.0
93	210	2.08	2.0	100	25	30.0	2	13.879	0.634	4.6	10.6
94	210	2.08	4.0	100	30	45.0	3	18.204	0.752	4.1	11.9
95	210	2.08	4.0	300	40	45.0	5	28.444	1.386	4.9	13.8
96	210	2.08	1.0	300	15	75.0	2	14.428	0.503	3.5	9.3
97	210	2.08	2.0	300	25	45.0	2	16.382	0.663	4.0	12.2
98	210	2.08	1.0	500	15	40.0	2	16.881	0.698	4.1	13.6
99	210	2.08	2.0	500	20	55.0	1	7.654	0.422	5.5	10.3
100	210	2.08	4.0	500	40	35.0	3	20.657	0.365	5.3	14.0
101	210	2.08	2.0	500	25	42.0	2	13.495	0.817	6.0	14.9
102	2019	1.85	1.0	300	30	15.0	3	22.555	0.816	3.6	12.7
103	2019	1.85	2.0	300	45	20.0	7	39.809	1.407	3.5	10.8
104	2019	1.85	4.0	300	65	9.0	3	19.677	0.913	4.7	12.0
105	2019	1.85	1.0	500	40	15.0	4	28.398	0.978	3.4	11.2
106	2019	1.85	2.0	500	55	15.0	5	31.885	1.081	3.4	10.6
107	2019	1.85	4.0	500	75	10.0	8	56.411	1.746	3.1	10.7

APPENDIX B: DETERMINATION OF CONVECTION COEFFICIENT FOR COLDROOM 165

According to Vesilind (1990), the rate of freezing (dy/dt) for a thin layer of sludge can be predicted by the equation

$$\frac{dy}{dt} = \frac{\bar{h}_c (T_f - \bar{T}_{af})}{\rho_f L} \quad (B1)$$

where \bar{h}_c = the average convection coefficient ($W/m^2 \cdot ^\circ C$)

ρ_f = the density of ice (917 kg/m^3)

L = the latent heat of fusion (93 W-h/kg)

T_f = the freezing point of sludge ($0^\circ C$)

\bar{T}_{af} = the average air temperature in the coldroom ($^\circ C$).

By separating variables eq B1 becomes

$$\rho_f L dy = \bar{h}_c (T_f - \bar{T}_{af}) dt. \quad (B2)$$

At $t = 0$, $y = 0$, and when t = the freezing time t_f , y = the depth of frozen sludge, ϵ . Integrating eq B2 between these limits yields

$$\rho_f L \epsilon = \bar{h}_c (T_f - \bar{T}_{af}) t_f. \quad (B3)$$

By rearranging terms and solving for \bar{h}_c , the above equation becomes

$$\bar{h}_c = \frac{\rho_f L \epsilon}{t_f (T_f - \bar{T}_{af})}. \quad (B4)$$

Substituting the values for each constant and changing i_1 to minutes and ϵ to millimeters, eq 4 becomes:

$$\bar{h}_c = \frac{5118 \epsilon}{t_f (-\bar{T}_{af})}. \quad (B5)$$

To calculate \bar{h}_c we had to determine \bar{T}_{af} , t_f , and ϵ . \bar{T}_{af} was determined by setting coldroom 165 at $-14^\circ C$. The values for t_f and ϵ were determined by freezing a tray of distilled water. Both the tray and the distilled water were precooled to $0^\circ C$. The tray was removed at various time intervals and the depth of the ice layer was measured with calipers. The data from this analysis are shown in the table below. Based on these data the average convection coefficient was calculated to be $23.1 \text{ W/m}^2 \cdot ^\circ C$. This was the value used in eq B1 to predict the freezing times.

Table B1. Laboratory data on freezing distilled water at $-14^\circ C$.

Freezing time (min)	Ice depth (ϵ) (mm)	Conv. coefficient ($W/m^2 \cdot ^\circ C$)
15	1.01	24.6
20	1.13	20.6
30	1.95	23.8
40	2.63	24.0
45	2.50	20.3
60	4.43	27.0
60	2.98	18.2
80	5.72	26.1
Avg.		23.1
s.d.		3.1

APPENDIX C: FREEZING TEST DATA FOR SIX-MILLIMETER LAYER OF ALUM SLUDGE

Test no.	Solids content (%)	Temperature (°C)	Predicted freezing time (min)	Actual freezing time (min)	Weight of frozen sludge (g)	Actual freezing rate (kg/h-m ²)	Effective grain size (D10) (mm)	Uniformity coefficient C _u
T1	2-3	-5	270.7	238	551	1.389	0.144	3.7
T2	2-3	-5	270.7	255	587	1.381	0.123	4.1
T3	2-3	-5	270.7	275	690	1.506	0.130	4.2
T4	2-3	-14	96.7	145	549	2.273	0.112	3.9
T5	2-3	-14	96.7	145	614	2.542	0.102	4.3
T6	2-3	-14	96.7	154	676	2.632	0.121	3.3
T10	2-3	-23	58.9	76	627	4.948	0.101	3.8
T11	2-3	-23	58.9	76	575	4.536	0.098	3.8
T12	2-3	-23	58.9	76	550	4.340	0.083	4.4
T13	2-3	-30	45.1	61	719	7.072	0.077	4.1
T14	2-3	-30	45.1	56	525	5.623	0.078	3.9
T15	2-3	-30	45.1	55	469	5.121	0.084	4.1
6%A	6-7	-23	58.9	70	578	4.955	0.150	3.7
6%B	6-7	-23	58.9	70	613	5.250	0.177	3.4
6%C	6-7	-23	58.9	70	530	4.539	0.182	3.4
6%D	6-7	-14	96.7	125	482	2.314	0.174	3.2
6%E	6-7	-14	96.7	125	591	2.836	0.182	3.3
6%F	6-7	-14	96.7	125	447	2.145	0.162	3.3
6%G	6-7	-5	270.7	240	602	1.505	0.194	3.4
6%H	6-7	-5	270.7	240	511	1.279	0.185	3.1
6%I	6-7	-5	270.7	240	405	1.012	0.184	3.0
6%J	6-7	-30	45.1	45	480	6.400	0.137	3.6
6%K	6-7	-30	45.1	60	671	6.714	0.138	3.0
6%L	6-7	-30	45.1	60	563	5.627	0.140	3.3
12%A	12-13	-30	45.1	38	502	7.918	0.151	2.75
12%B	12-13	-30	45.1	38	490	7.738	0.152	2.89
12%C	12-13	-30	45.1	48	658	8.226	0.148	2.87
12%D	12-13	-23	58.9	57	565	5.946	0.154	2.85
12%E	12-13	-23	58.9	52	474	5.472	0.153	2.91
12%F	12-13	-23	58.9	62	701	6.783	0.168	2.91
12%G	12-13	-14	96.7	88	548	3.736	0.171	3.14
12%H	12-13	-14	96.7	80	545	4.091	0.174	3.10
12%I	12-13	-14	96.7	100	642	3.853	0.183	3.16
12%J	12-13	-5	270.7	192	483	1.509	0.198	3.14
12%K	12-13	-5	270.7	182	463	1.526	0.185	3.04
12%L	12-13	-5	270.7	199	582	1.754	0.192	3.18

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